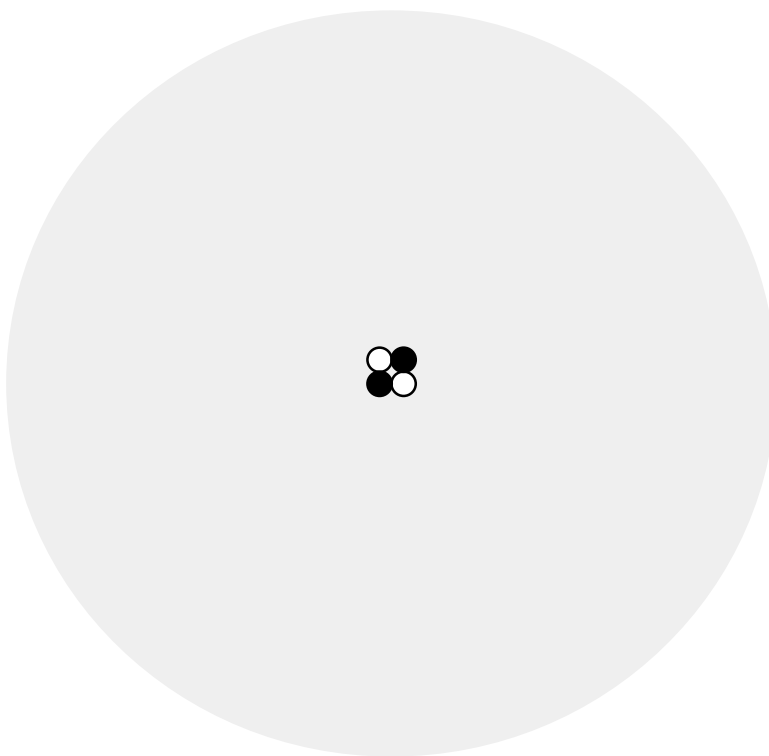


Introduction

This is a non-standard introduction to the standard model. It starts with a tour of the Helium atom, detours briefly to talk about electrons as magnets, and then plays "Connect the dots" for a while. This leads us to the idea of quarks in much the same way as they were originally thought of. After quarks, leptons! Bosons! Antimatter!

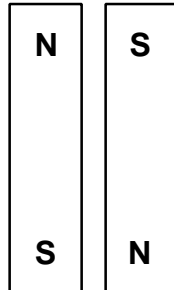
The Helium Atom

A Helium atom is composed of two electrons on the outside, and a nucleus on the inside, which has two neutrons and two protons. Sort of like this:

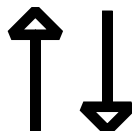


The two electrons are both moving around the nucleus in the same way; the technical term is to say that they are in the same orbital. There is a great deal to be said about how they move, as this motion is quantum mechanical, but not today. That is why I drew the electrons as a big blur. The interesting detail I wish to focus on is that the two electrons are arranged in a certain way, and this

stems from the fact that an electron is a tiny magnet, with a north and a south pole. The two electrons move in such a way as to keep the north end of one electron near (so to speak) the south end of the other and vice-versa:



Or perhaps it is better to draw something like this :



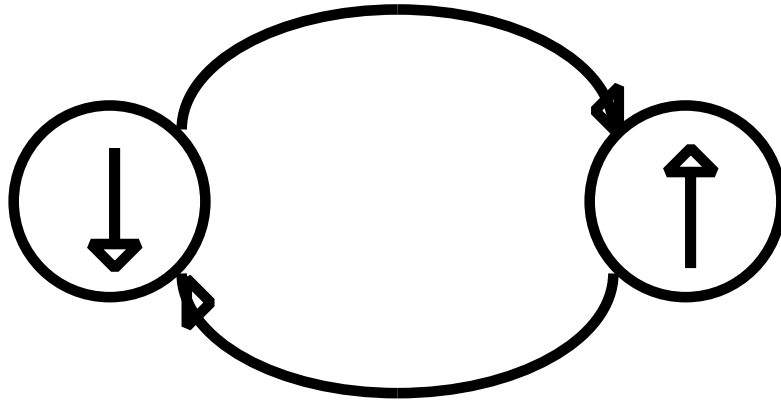
Drawing the arrangement of the electrons in this second, more abstract way invites us to draw analogies with other arrangements where one thing is pointing up and another thing is pointing down. One example might be two pennies sitting on a tabletop, with one of them face up and the other face down. As it happens, there is nothing to prevent the two pennies from being face up; for the Helium atom, if the two electrons are made to face the same way, the atom flies apart and it becomes a He^+ ion.

Onward and inward! In the center of the Helium atom is the nucleus, and it has two protons and two neutrons. The proton and the neutron are nearly the same. Not quite, but almost. They both have about the same mass (938 MeV for the proton, 940 MeV for the neutron), and they are both about 10^{-15} m across. What if the proton and the neutron are like the two faces of the penny -- that is, in some way, fundamentally the same object which has two different states? Call this particle the nucleon -- when the nucleon is face up, it is a proton. When the nucleon is face down, it is a neutron. This idea, known as isospin symmetry, is one of the more useful ideas that we have to understand nuclei and particles. Once we understand more about what is inside the proton and the neutron, it will become apparent that they are not really the same

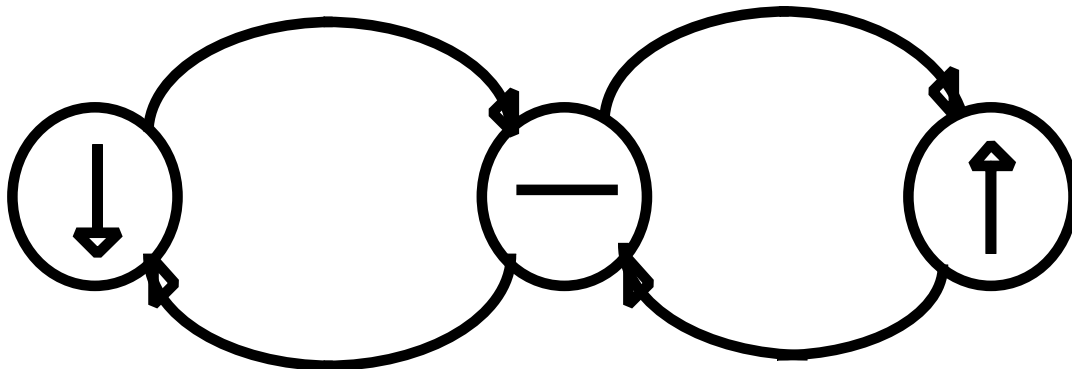
particle, but the ideas that we come up with while thinking that they are still useful.

Connecting the dots

Let us just think about a single electron, or penny, or neutron. It has two states, and there is a way to flip between these two states:

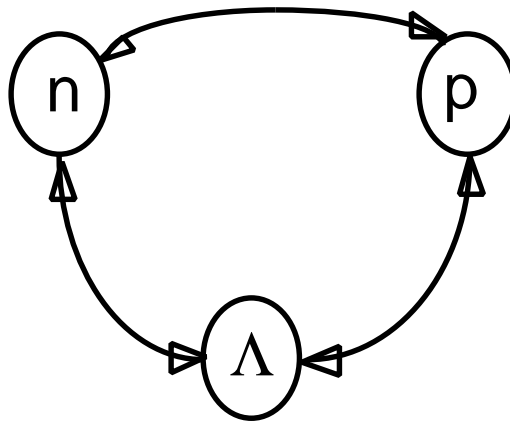


Pretty boring. Let's try something with more possibilities. What if there are three states?



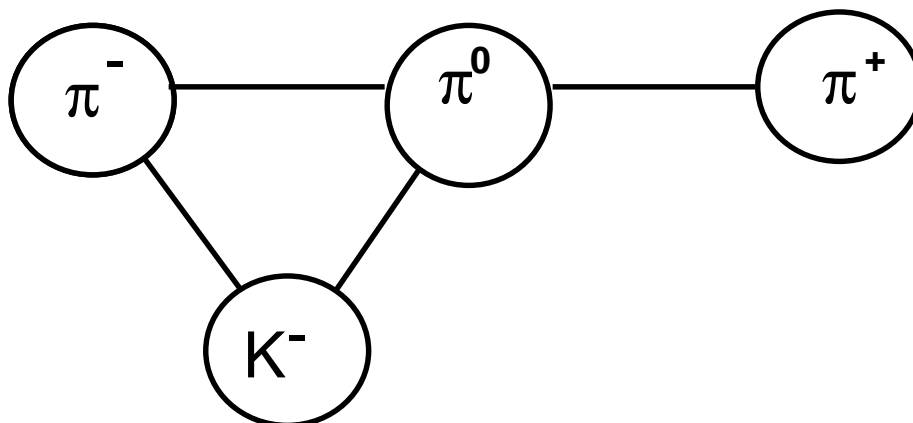
What can this correspond to? Well, this might describe one of the old French 10 franc coins, which are so thick that they stand easily on its side. It doesn't describe an electron or a nucleon, but it does describe another kind of particle, called a pion. There are three kinds of pions: positive, negative, and neutral. As in the case with the nucleon, changing from one state to the other changes the electrical charge.

In the mid-1960's, it became apparent that there was some other quantity besides electric charge that elementary particles had. It was not very clear what this property was, exactly; particles that had it did not decay for a long time, and for lack of any better name it was called strangeness. For example, there is a particle, called the lambda, which is about the same mass as a nucleon, (well, a little bit more massive) but it has a unit of strangeness. It also has no units of electrical charge. It was perhaps first Gell-Mann or Zweig who drew the following sort of diagram on some chalkboard somewhere:



The connection between the neutron and the proton is one of three possible kinds of connections; there is a similar connection between the neutron and the lambda, which changes the strangeness and not the electric charge, and also a connection between the proton and the lambda, which changes both the charge and the strangeness.

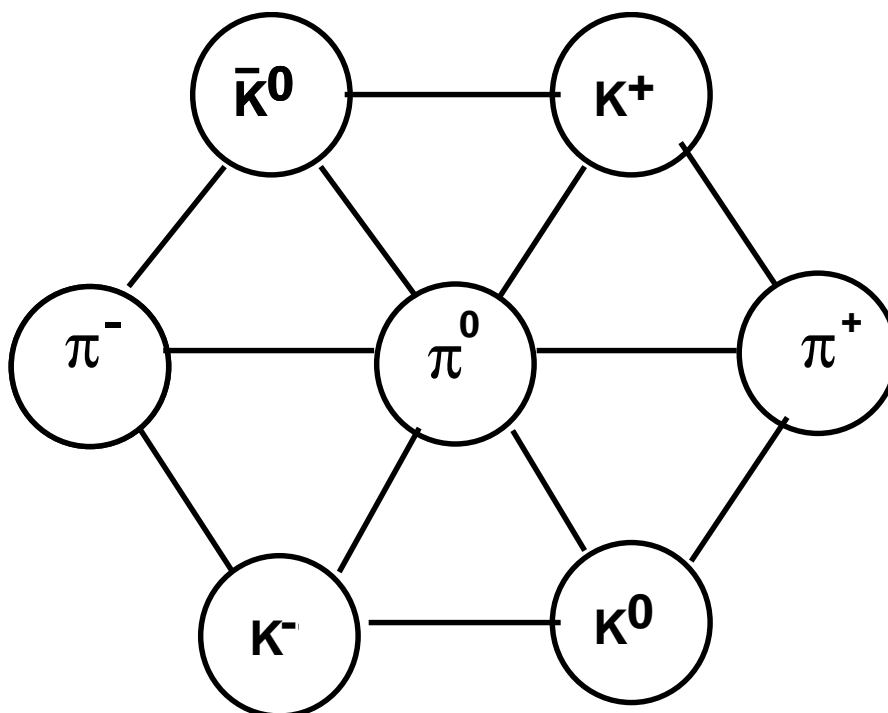
There are particles like pions which have strangeness also; they are called kaons. They are somewhat heavier than pions, just as the lambda is a bit heavier than the nucleons. Let us start with the negatively charged kaon:



Now you might try to put the positive kaon below and to the right of the positive pion, in which case the neutral kaon would have to go somewhere between the positive and negative kaons. But the experiments do not tolerate this kind of theory, and so this possibility must be discarded. There are two different neutral kaons, and that is just a fact. Actually, the study of the neutral kaons is an interesting affair, and it is a very active field of research. But that is a story for a different day. For today, we can complete the chart once we have a different experimental result in front of us:

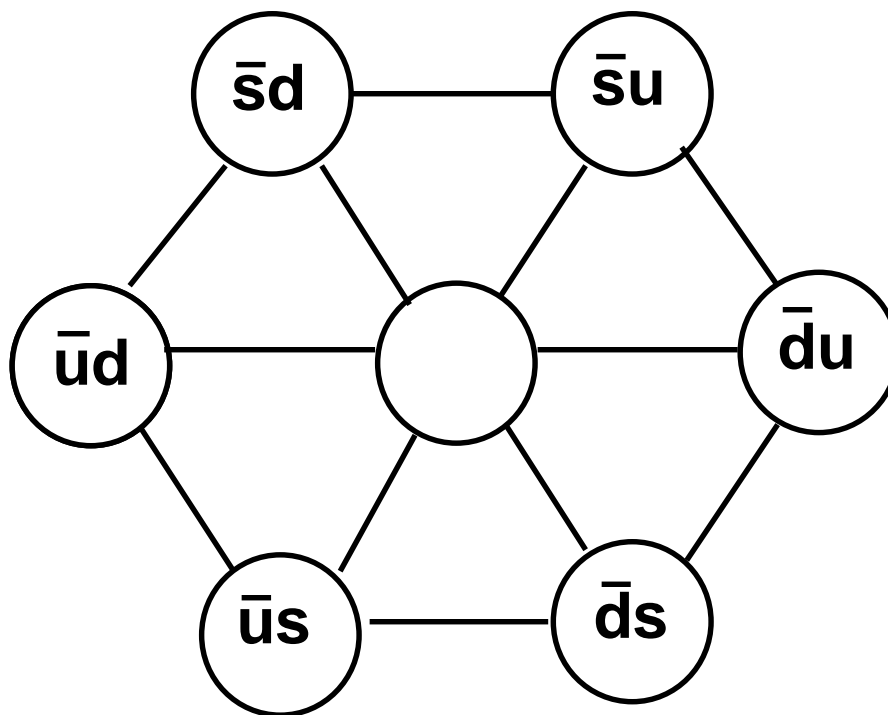
$$\phi^0 \rightarrow K^+ K^-$$

Which is to say that in the lab we observe a neutral particle which we call the phi, which decays into a pair of oppositely charged kaons. If strangeness is conserved the way that charge is (and it is not certain at this point that this is true), and if we say that the negative kaon has one unit of strangeness (since it sits in the diagram in sort of the same way that the lambda sits in its diagram) then maybe the positive kaon has one unit of anti-strangeness! In that case, there is also space on the diagram for two neutral kaons as well. The two neutral kaons are opposites in the same sort of way that positive and negative kaons are. They are antiparticles - one is the antimatter form of the other. More on antimatter some other day!



The quarks

Over a period of time ranging from the mid 1960s to the mid 1970s, the idea that these diagrams reflect some internal components of subatomic particles became accepted. I don't want to make this sound simple; it was actually fairly difficult. The inventor of the term quark, Murray Gell-Mann, was of the view that they were not physical objects, but rather mathematical abstractions. Some difficulties with the quark scheme and a well-known law of quantum mechanics called the Exclusion Principle appeared, and by 1969, textbooks were being printed that said quarks could not be the right explanation. When the first experiments showing that there were indeed point like objects inside of protons were done, we preferred to call them partons, since we were not so certain about these quarks. Hindsight is always much clearer. Here is the diagram for the kaons and the pions, showing their quark structure:



Each of the mesons (as this kind of particle is called) is made of a quark and an antiquark; the antiquark is written with a bar over it. The pions and kaons are made of three different kinds of quarks, called an up quark, a down quark, and a strange quark. The names up and down are from analogy with the arrangement of the electrons in the Helium atom; the name strange is from the way in which the first particles which had this property seemed to their discoverers. Moving to the right on the chart turns a down into an up or an anti-up into an anti-down; moving to the lower right turns a down into a strange, or an

anti-strange into an anti-down. Moving to the lower left turns an up into a strange or an anti-up into an anti-strange. Now -- what should go in the middle bubble? How many neutral mesons should there be? Can you find out their names? And for extra credit, which particle is made of a strange and an anti-strange quark?

The proton, as it turns out, is made of two up quarks and one down quark, and the neutron from one down and two up quarks. The lambda is made of one of each of the three kinds. From this you can figure out what the charges of the three quarks are -- remember, the lambda is electrically neutral.

There are a host of different possible combinations of quarks, and a host of different particles, and for the most part, it is clear which combination of quarks forms which particle. There are a few interesting cases where it is not quite certain yet. All of these particles are either:

- 1). A set of three quarks -- these are called baryons;
- 2). A set of three anti-quarks -- anti-baryons, or
- 3). A quark and an anti-quark -- these are called mesons.

Why are only these combinations allowed? Well, it has to do with the force that holds them together. In gravity, there is only one kind of thing that the object has that makes it sensitive to the gravitational force, and that is the mass. In electricity, there are two such things. An object can be positively charged or negatively charged. In the force that holds quarks together, there can be three such things. We call them color; a particle can be red or green or blue, just as it can be positive or negative or massive. The rule seems to be that in order for a quark combination to be a particle that you can see in the lab, it must have no net color -- so a meson might be a red and an anti-red, and a proton might be a red, a green and a blue. That is a nice explanation, but it leads to another question: Why are there no colored particles?

Well, for that matter, why are there charged particles? Why does not every electron settle down around some nucleus and leave the entire universe with only neutral particles? Hum. . . it does not take very much energy to ionize an atom, actually. Maybe the reason why there are no colored particles is that it takes a great amount of energy to remove a quark from a nucleon. Suppose that the force law for two quarks is like $\mathbf{F} = -k\mathbf{x}$, like a spring, rather than

$\mathbf{F} = q_1q_2 / (\mathbf{x}^2)$, as is the case for the electric force. Then, as two quarks are pulled apart, the energy that goes into separating them becomes so big that at some point it is enough energy to create some mass. $E=mc^2$, and with enough E , you can create some mass in the form of some new quarks. These new quarks which pop out of the energy in the spring then get pulled towards the original two quarks and they form two new particles, each of which is colorless.

In 1974, a new quark was discovered. We call it charm, and it is what we call a heavy quark. The up and the down quark are only a few MeV, and the

strange quark is a few hundred, but the charm quark is about 1500 MeV -- more than a proton, which is made of three light quarks! It has the same charge as the up quark. A few years later, another new quark, with a mass of about 5000 MeV was discovered, here at FermiLab; and just recently, the sixth quark was also found here, with a mass of 170000 MeV. We call them the bottom (it has the same charge as the down quark), and top quark (charged the same as the up), respectively.

The Leptons

The particles which are made out of quarks are called hadrons. Notice that (going back to the Helium atom) there is a very common particle which is not a hadron at all -- namely, the electron. If the electron were a quark, then the force which pulls quarks together (it is called the strong force) would pull it right into the nucleus. The electron is also quite light; it is about 1/2 MeV. It is called a lepton. There is an antimatter version of the electron as well, called a positron. It is just like the electron, except that it has a positive charge; if it collides with an electron, they both disappear. There are also particles called muons, which are produced in the upper atmosphere and passes through the atmosphere into the earth. The muon (the symbol is μ) seems to be pretty much like an electron, except that it is more massive. There also seems to be a particle called a neutrino, which is like an electron but with no electric charge at all -- which makes it pretty hard to detect! The symbol for a neutrino is ν .

OK. Time for one of those experimental facts again. The following reaction occurs, although not very often:

$$p \rightarrow e^- \bar{\nu}$$

That is, a meson made of a down quark and an anti-up quark decays into an electron and an anti-neutrino. It is as if there is some analogy between the up-down pair and the neutrino-electron pair.

up : down is like neutrino : electron

Hum . . . remember how there are several different quarks, which seem pretty similar, except that they have different masses? And likewise, the muon is like the electron, except that it has more mass? Maybe we can extend this analogy, with a different line for different sets of masses:

up	:	down	is like	neutrino	:	electron
charm	:	strange	is like		:	muon
top	:	bottom	is like		:	

But . . . the most common decay of the pion is into a muon and an anti-neutrino:

$$\pi^+ \rightarrow \mu^+ \bar{\nu}$$

If the analogy is right, it should decay into a muon and some other particle. That other particle should be like an anti-neutrino, but maybe with a different mass.

This is the sort of problem that can only be solved by an experiment. Take a bunch of pions. Let them decay into muons, and throw out all the cases where they decay into electrons. Take the neutrinos from these decays and run them into a large piece of metal, where maybe the reaction might be forced to go backwards as the neutrinos strike the quarks in the metal. Do you get any electrons out? If not, then the neutrino from the muon is really a different particle than the neutrino from the electron.

This experiment was done, in the early 1960s, by Leon Lederman, Jack Steinberger, and Mel Schwartz. There are indeed different kinds of neutrinos - we call them electron neutrinos and muon neutrinos.

Now the table is nearly filled -- except for the third generation of leptons. Is there a particle like the electron and the muon, except heavier? Once again, this is one of those questions that no amount of theory will answer -- but an experiment does! The third generation lepton is called the tau, and it has also a third kind of neutrino. The tau was first seen by Martin Perl in 1975, and the tau neutrino was seen by a collaboration of 54 physicists working at Fermilab in 2000.

Here is our final table, with masses and charges filled in. Quarks are on the left, and leptons are on the right.

up charge $2/3$ mass ~ 0	down charge $-1/3$ mass ~ 0	electron neutrino charge 0 mass 0	electron charge -1 mass 0.5 MeV
charm charge $2/3$ mass 1500 MeV	strange charge $-1/3$ mass $\sim 300 \text{ MeV}$	muon neutrino charge 0 mass $0 ?$	muon charge -1 mass 106 MeV
top charge $2/3$ mass 170000 MeV	bottom charge $-1/3$ mass 5000 MeV	tau neutrino charge 0 mass $0 ?$	tau charge -1 mass 1777 MeV

All of these particles are of the type called fermions, and furthermore, they are fundamental -- we do not know of any inner structure to these particles. Furthermore, if there are more fundamental fermions than these, they must be extremely heavy, or else they would have appeared in someone's experiment by now. You might reasonably ask a great number of questions here, such as: Why are there three generations? Why does each generation have four types of particles? Why are the masses like that? Why are the charges like that? Why do some of the fermions have color while other ones do not? Why are the charges of the leptons three times that of the quarks? Well, your guess is as good as mine. There are a *lot* of totally unanswered questions in particle physics these days - and that is why we are doing all of these experiments!

The Bosons

Apart from the fermions, there is a second type of fundamental particle, called the boson. The bosons are associated with forces. There are five different kinds of fundamental bosons, maybe.

The boson for the electromagnetic force is the photon, which is a particle of light, i.e., a particle of an electromagnetic field. Time for a small detour now.

A small detour : A box 'o photons.

Think of a pendulum . . . to be specific, let us say that a 1 kg mass is hung from a thin light wire of 1m length. The energy of this pendulum is given by

$$(g/2) (x^2) + (1/2) (v^2)$$

where **g** is the acceleration from gravity, **x** is the position of the weight, and **v** is its velocity. From Newton's three laws of motion, there is no reason to say that this quantity has to be any specific number, except that it obviously can not be negative. However, the laws of quantum mechanics say that the energy has to be one of the following numbers:

$$1/2 \text{ D}$$

$$3/2 \text{ D}$$

$$5/2 \text{ D}$$

$$7/2 \text{ D}$$

·
·
·

where **D** is a number that depends on the length of the string and the strength of gravity and a number called Plank's constant. In this particular case, **D** is 330×10^{-36} Joules, which is very small. When the energy changes by this amount, we say that the pendulum has absorbed a quantum of energy; if the pendulum loses **D**, we say that it has emitted a quantum of energy.

Now think about a square hollow metal box. Inside of the box, there can be electric and magnetic fields. The energy of the fields is given by

$$(C_1) (E^2) + (C_2) (B^2)$$

where **C₁** and **C₂** are constants of no particular interest, **E** is the electric field at the center of the box, and **B** is the magnetic field at the center of the box. Notice the similarity with the pendulum. Again, quantum mechanically, the energy can only take values of $1/2 \text{ D}$, $3/2 \text{ D}$, etc. The value of **D** is different from the previous case, but we still speak of the field emitting and absorbing quanta. In the case where the field is electromagnetic, the quanta are called photons. To actually get energy out of the box 'o photons, you must put a hole in the side of course.

OK, where were we? Ah yes, the (maybe) five bosons. Right. The boson for the electromagnetic force is the photon; for the strong force which holds the quarks together, it is the gluon. For the gravitational force, it is called the graviton, but so far, the theory of gravitational particles does not work very well,

and no one has observed any gravitons. There is yet another force which I have not said much about, called the weak force, and it has two kinds of bosons: the W and the Z. The W is charged, and the Z is neutral. Unlike all the other bosons, the Z and the W have mass -- some 97 and 86 times the proton mass, respectively.

I should also mention the (as of yet) hypothetical boson called the Higgs. The Higgs is the result of the simplest explanation that anyone has thought of for why particles have mass. Mind you, the Higgs mechanism does not predict what the mass of any particle is, nor does it predict the mass of the Higgs boson itself. Just understanding why particles have mass is hard enough, never mind how much! There are also several variations of the Higgs mechanism, which predict different numbers of Higgs bosons -- sometimes neutral, and sometimes charged. Again, this is one of those things which can only be discovered, and not deduced. And indeed, a large fraction of the particle physicists in the world today are out there looking for the Higgs.

What about the strengths of these various forces? The strong force, which holds together the quarks, is roughly a hundred, or 10^2 , times as strong as the electromagnetic force. It is about a billion, or 10^9 , times as strong as the weak nuclear force. It is about 10^{43} times as strong as the force of gravity.

But these "typical" numbers conceal a lot of ugly details. To be more accurate, each fermion has some different degree of coupling with each boson. For example, the electron has a certain electrical charge. What that means is that it has a certain tendency to react with an electromagnetic field - *i.e.*, with a photon. Consider the case where a photon lands on a piece of metal; the electromagnetic fields of the photon can push an electron out of the metal, because the electron has some electric charge. That photon will never push a neutrino out of anything however, because the neutrino is neutral. In the same way, a gluon will not exert any force on either an electron or a neutrino, but it will interact with quarks. So to be accurate, we have to list all of the interaction strengths for all the possible bosons with all the possible fermions.

Actually, it is worse than that. Sometimes a boson can interact with another boson - for example, since the W boson has an electric charge, photons can interact with it.

In fact, it is even worse than that, because the interaction of the Z and W bosons with the fermions depends on which way the fermion is spinning. Every fermion has some angular momentum, as if it were spinning around. If you imagine a fermion moving directly towards you, it might have a clockwise spin or it might have a counterclockwise spin. The Z and W bosons have different couplings to the different spin cases.

There are nine different numbers which characterize the different way that all the bosons and fermions interact; one each for the strong, electromagnetic,

and gravitational forces, and six for the weak nuclear force. Furthermore, of the six for the weak force, four apply only to interactions with quarks, and not to leptons at all.

You might reasonably ask a great number of questions here, such as: Why are there five bosons? Why are two of them so massive, when the others are massless? Why are there so many constants for the weak force, but not the other forces? Why do the weak interactions with quarks need four more numbers? What are the specific values of the numbers, and why do they have those values? Well, your guess is as good as mine. There are a *lot* of totally unanswered questions in particle physics these days - and that is why we are doing all of these experiments!